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SCO X-1:

ORIGIN OF THE RADIO AND HARD X-RAY EMISSIONS

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### Abstract

The consequences of models for the central radio source and the hard X-ray ( $> 30$  keV) emitting region in Sco X-1 are examined. The radio emission could result from noncoherent synchrotron radiation and the X-rays may be produced by bremsstrahlung. We show that both these mechanisms require a mass outflow from Sco X-1. The radio source is located at  $r \simeq 3 \times 10^{12}$  cm from the center of the star, and its linear dimensions do not exceed  $3 \times 10^{13}$  cm. The magnetic field in the radio source is on the order of 1 gauss. If the hard X-rays are produced by thermal bremsstrahlung, their source is located at  $10^9 \lesssim r \lesssim 5 \times 10^9$  cm, the temperature is  $2 \times 10^9$  K, and the emission measure is  $2 \times 10^{56} \text{ cm}^{-3}$ . This hot plasma loses energy inward by conduction and outward by supersonic expansion. The rates of energy loss for both these processes are about  $10^{36} \text{ erg s}^{-1}$ , comparable to the total luminosity of Sco X-1.

The outward mass flow has the following consequences: It maintains the magnetic field in the radio source which would otherwise fall off as  $r^{-3}$  and could not account for the radio emission. It ionizes the interstellar medium in the vicinity of Sco X-1, thereby producing H $\beta$  emission consistent with observations. The lower limit on the energy deposited by charged particles in the vicinity of Sco X-1, as obtained from the observed H $\beta$  emission, is about  $3 \times 10^{35} \text{ erg s}^{-1}$ . The mass loss of Sco X-1 is  $\sim 3 \times 10^{-8} \text{ M}_{\odot}/\text{year}$ .

## I. INTRODUCTION

Radio emission from the vicinity of Sco X-1 was first detected by Andrew and Purton (1968) at 4.6 cm and subsequently by Ables (1969) at 6 cm. Hjellming and Wade (1971), using interferometric observations at 3.7 and 11.1 cm, showed that there are three radio sources close to Sco X-1. Two of these are separated by about one to two minutes of arc from the X-ray star; the third source coincides in position with Sco X-1. While the two lateral sources do not show temporal variations, the central source is highly time variable (Wade and Hjellming 1971). Because of the geometry of the system, the association of the lateral sources with Sco X-1 is suggestive but by no means proven.

Sco X-1 was also observed at 21.2 cm by Braes and Miley (1971). These observations have confirmed the triple structure of the radio emitting region as well as the variability of the central source. The observed flux densities of the lateral sources at 21.2 cm, 11.1 cm and 3.7 cm yield a spectrum of the approximate form  $\nu^{-1}$  in the  $10^9$  to  $10^{10}$  Hz region. Because of its variability, an accurate spectral form cannot be derived for the central source.

Upper limits on radio emission from Sco X-1 at longer wavelengths were set by Jauncey (1971) at 408 MHz, by Apparao (1971) at 327 MHz, and by Slee and Higgins (1971) at 80 MHz. When combined with the higher frequency measurements, these measurements imply that at least one of the lateral sources, and possibly also the central source, are optically thick or suppressed below  $\sim 10^9$  Hz.

There is only one spatial component for the X-ray emission from Sco X-1, and it coincides with the central radio source (Hjellming and Wade 1971). The X-ray emission, however, may be divided into two spectral components: a main component (e.g. Gorenstein, Gursky and Garmire 1968) with  $T \sim 4 \times 10^7 \text{K}$ , and a hard component which dominates the X-ray spectrum above about 40 keV (Peterson and Jacobson 1966, Buselli et al. 1968, Riegler, Boldt and Serlemitsos 1970, Agrawal et al. 1971, Haymes et al. 1972). Both these components show temporal variations, but while the main emission does not vary by more than 50% to 100% (Canizares et al. 1973), the hard component was observed to vary by as much as a factor of 3.

It is known (Canizares et al. 1973) that the temporal variations in the radio emission and in the main X-ray component are uncorrelated. Since there are no simultaneous radio and hard X-ray measurements, no statement can be made on the correlation between these two components.

The physics of the main component of X-ray emission from Sco X-1 was discussed in detail in the literature (e.g. review by Oda and Matsuoka 1970). From a recent study (Kitamura et al. 1971) a possible model is one in which the continuum, extending from the infrared and optical to these X-rays, is produced by thermal bremsstrahlung in a plasma of density  $\sim 3 \times 10^{16} \text{cm}^{-3}$  and temperature  $\sim 4 \times 10^7 \text{K}$ , confined in a spherical volume of radius  $\sim 4 \times 10^8 \text{cm}$ . These values were obtained by taking into account the distortion of the spectrum due to

electron scattering, and thus the temperature is somewhat lower than the value obtained without this correction.

The physical properties of the radio emitting region in Sco X-1 were investigated by Riegler and Ramaty (1969). These authors showed that if the radio emission is noncoherent sychrotron emission, consideration of equipartition and selfabsorption requires that the radiation be produced in a magnetic field greater than a few gauss, and at a distance greater than about  $10^{12}$  cm from the center of the star. Thus, the radio emission appears to be produced at a much larger distance than the main X-ray emitting region, a fact which is consistent with the lack of correlation between these two components.

The purpose of the present paper is to examine the origins of the radio emission and hard X-rays from Sco X-1. Even though there is no compelling observational data (e.g. correlated time variations) to suggest a common origin for these emissions, we were prompted to consider this possibility because of the analogy with solar flares. It is well known that the microwave and hard X-ray emissions from solar flares exhibit an excellent temporal correlation (Kundu 1961). There may be similarities between the radio and hard X-ray emissions from Sco X-1 as well. More important, however, the assumption that the radio emission is sychrotron radiation and that the X-rays are bremsstrahlung has a very interesting consequence: It predicts that the atmosphere of Sco X-1 will expand supersonically in a manner

analogous to the expansion of the solar corona. Such an expansion leads to a stellar wind which can ionize the interstellar medium out to a few parsecs from Sco X-1, consistent with observations of  $H\beta$  emission from the vicinity of this object (Johnson 1971). It seems also possible that such a stellar wind could be the cause of the two lateral radio sources of Sco X-1. We shall not explore this particular consequence, however, because any model building requires some rather arbitrary assumption on the mode of mass flow from the star.

## II. PHYSICAL PROPERTIES OF THE RADIO SOURCE

We consider the physical properties of the central radio source. Let us first summarize the observational parameters which we shall use in the subsequent discussions.

The radio emission from the central source is highly variable. At 2695 MHz and 8085 MHz, Wade and Hjellming (1971) observed several flares of duration greater than a few hours. For one of these flares (February 26, 1971) the peak flux density was greater than 0.26 f.u. and the rise time was about one hour or less. At 1415 MHz the flux density was observed to vary from about 0.06 f.u. to less than 0.01 f.u. in about 3 hours (Braes and Miley 1971). In the calculations below we use a flux density of 0.03 f.u. at  $10^9$  Hz. This represents a possible average which is likely to be exceeded during major flares.

The distance to Sco X-1 is uncertain. Sofia, Eichhorn and Gatewood (1969) have measured the proper motion of Sco X-1 and found

that it agrees with the proper motions of members of the Sco-Cen association. This implies that Sco X-1 is at 170 pc, the distance to this association (Bertiau 1958). This line of argument was criticized most recently by van Altena (1972), and it is possible that Sco X-1 is at a larger distance (e.g. Wallertstein 1967, Hiltner and Mook 1970). However, we use  $d = 170$  pc in the subsequent calculations because our conclusions do not depend critically on the distance.

Let us assume that the radio emission is noncoherent synchrotron radiation. If the radio source is a spherical volume of radius  $r$  containing energetic electrons of differential number density  $A(\gamma-1)^{-\Gamma}$ , where  $A$  is a constant,  $\gamma$  is the electron Lorentz factor and  $\Gamma$  is the spectral index, then the flux density at a distance  $d$  from the source is given by (e.g. Ramaty 1971)

$$S(\nu) \approx 10^{-23} \frac{4(\pi/3)r^3}{d^2} (0.06)^{\Gamma-1} B_{\perp}^{(\Gamma+1)/2} (10^9/\nu)^{\Gamma-1}/2. \quad (1)$$

Here  $S$  is in  $\text{erg cm}^{-2} \text{ s}^{-1} \text{ Hz}^{-1}$ ,  $r$  and  $d$  are in cm,  $B_{\perp}$  is the perpendicular component of the magnetic field in gauss, and  $\nu$  is the frequency in Hz. In terms of the assumed spectral form, the density of energetic electrons with energies above a given value is

$$n_r(>\gamma) = A(\gamma-1)^{-\Gamma+1} (\Gamma-1)^{-1} \quad (2)$$

where  $n_r(>\gamma)$  is in  $\text{cm}^{-3}$ .

The flux density as given in equation (1) does not take into account the various absorption and suppression effects that influence



a synchrotron source at low frequencies. These effects are absorption below the plasma frequency (P), synchrotron selfabsorption (SA), the Razin effect (R), and gyroresonance absorption (GR) (e.g. Ramaty and Petrosian 1972). The corresponding turnover frequencies, i.e. frequencies of unit optical depth, are

$$\nu_P \approx 9 \times 10^3 \nu_n, \quad (3)$$

$$\nu_{SA} \approx 3 \times 10^{12} \left( \frac{S}{\Omega} \right)^{2/5} B_{\perp}^{1/5} \quad (4)$$

$$\nu_R \approx 20n/B_{\perp}, \quad (5)$$

where  $n$  is the density of the ambient electrons in  $\text{cm}^{-3}$ ,  $S$  is the observed flux density at  $\nu_{SA}$ , and  $\Omega = \pi r^2/d^2$  is the solid angle in steradian subtended by the source. All frequencies in equations (3), (4) and (5) are in Hz.

Gyroresonance absorption (e.g. Takakura and Scalise 1970) is absorption of radio emission at the harmonics of the gyrofrequency of the ambient electrons. In solar flares, where the temperature of the ambient plasma does not exceed a few times  $10^7 \text{K}$ , gyroresonance absorption is important only up to the third or fourth harmonic of the gyrofrequency. For Sco X-1, however, the ambient plasma in the radio source could be at a higher temperature, and thus gyroresonance absorption could be important at higher harmonics as well. In Appendix A we give the details of the evaluation of the gyroresonance absorption coefficient due to electrons with a Maxwell-Boltzman distribution at temperature  $T$ . We find that the absorption coefficient is

approximately

$$\alpha(\nu) \approx 2 \times 10^5 n B \nu^{-2} I(\nu/\nu_B, T) \quad (6)$$

where  $\alpha$  is in  $\text{cm}^{-1}$ ,  $n$  is in  $\text{cm}^{-3}$ ,  $B$  is in gauss and  $\nu$  is in Hz.

Numerical values for the function  $I$ , defined in equation A3, are given in Table 1 for  $T=2 \times 10^9 \text{K}$ .

Consider now the results of Figure 1 which shows various relationships between the radius  $r$  of the radio source and the perpendicular component of the magnetic field,  $B_{\perp}$ . The light solid lines are the loci of constant  $n_r(>30 \text{keV})$  for a fixed flux density at a given frequency. These lines are obtained from equations (1) and (2) for  $S(10^9 \text{Hz}) = 3 \times 10^{-25} \text{ erg cm}^{-2} \text{s}^{-1} \text{Hz}^{-1}$  and  $\Gamma = 3$ . As mentioned in the introduction, the spectral index of the central source cannot be well determined. An index  $(\Gamma-1)/2 = 1$  is a reasonable fit to both lateral sources and is not inconsistent with the available data for the central source. We have extended the electron spectrum down to 30keV because evidence for the existence of such electrons is provided by the hard X-rays to be discussed in Section III.

The line LT represents the upper limit on the size of the source consistent with the observed temporal variations of the radio source. According to Wade and Hjellming (1971), the characteristic rise times of the radio flares is about one hour or less. The line LT in Figure 1 corresponds to  $r = ct$  with  $t = 10^3$  seconds. It should be noted that a rapid time variation in the 30 to 50 keV X-ray emission for Sco X-1

was observed by Agrawal et al. (1969). The time scale of this variation is also on the order of  $10^3$  seconds. The size of the hard X-ray emitting region should therefore not exceed that of the radio source. As will be shown later, however, it is probably much smaller.

The line SA is obtained from equation (4) with  $S = 3 \times 10^{-25}$  ergs  $\text{cm}^{-2} \text{sec}^{-1} \text{Hz}^{-1}$ ,  $\nu_{sa} = 10^9 \text{Hz}$  and  $d = 170$  pc. Because of the absence of selfabsorption at frequencies greater than  $10^9 \text{Hz}$ , the allowed values of  $r$  and  $B_{\perp}$  have to lie above and to the left of this line. The line R is obtained from equation (5) by setting  $\nu_R$  equal to  $10^9 \text{Hz}$  and  $n = n_r(>30 \text{keV})$ . The absence of a Razin cutoff at frequencies greater than  $10^9 \text{Hz}$  then implies that the allowed values of  $r$  and  $B_{\perp}$  are above and to the right of this line.

The lines EP and EP' represents the condition of equipartition between the energy densities in energetic electrons and the magnetic field of the radio source. For the electron spectrum given above, this condition is

$$\frac{B^2}{8\pi} = A m c^2 \int_{\gamma_1}^{\gamma_2} (\gamma^{-1})^{-\Gamma+1} d\gamma. \quad (7)$$

The limits of integration,  $\gamma_1$  and  $\gamma_2$ , were chosen as follows: for the line EP ( $>30 \text{keV}$ ),  $\gamma_1 = 1.06$  and  $\gamma_2 \rightarrow \infty$ , i.e. we consider equipartition with all electrons of energies greater than  $30 \text{keV}$ . For the line EP',  $\gamma_1 = 3 \times 10^{-4} \sqrt{\nu_1/B}$  and  $\gamma_2 = 10^{-3} \sqrt{\nu_2/B}$ , where  $\nu_1 = 10^9 \text{Hz}$  and  $\nu_2 = 10^{10} \text{Hz}$ , i.e. we consider equipartition only with the electrons which produce radio emission in this frequency range (Ginzburg and Syrovatskii 1964).

Let us now consider the results of Figure 1. An upper limit on the radius of the source,  $r < 3 \times 10^{13}$  cm, is set by the light traversal time. A lower limit on  $r$  is set by selfabsorption, but this limit depends upon the value of the lower limit on  $B_{\perp}$ . Such a lower limit can be obtained either by invoking an equipartition argument, or by obtaining independent information on the ambient electron density. The electron density can be estimated from a model for the hard X-ray emission which will be discussed later. Here we merely assume that the energetic electron spectrum extends down to 30keV and that the ambient electron density equals  $n_r(>30\text{keV})$ . Then the lower limit on  $B_{\perp}$  is determined via the Razin effect, and is given by the line R. In this case the allowed values of  $B_{\perp}$  and  $r$  lie between the lines LT and SA, and to the right of the line R. As can be seen, these values satisfy both equipartition conditions given above.

The line  $B \propto r^{-3}$  in Figure 1 is the dipole magnetic field that one would expect under static conditions at a distance  $r$  from an object of radius  $10^9$  cm and surface field  $10^6$  gauss. As can be seen, this field is not sufficient to account for the radio emission. However, if there is a mass flow from the central object, magnetic field will be transported by the outflowing plasma to large distances from it, and  $B$  will vary as  $r^{-x}$  where  $1 \leq x \leq 2$ . In this case a field of  $\sim 1$  gauss at  $\sim 10^{13}$  cm, for example, requires a surface field of  $\sim 10^{4x}$  gauss at  $10^9$  cm and  $10^{7x}$  gauss at  $10^6$  cm. These surface fields could be consistent with both neutron stars or white dwarfs. We conclude,

therefore, that the observed radio emission from the central source of Sco X-1 cannot be explained by noncoherent sychrotron radiation, unless there is a mass outflow from the object. As we shall show in the next section, such a mass flow is the consequence of a bremsstrahlung model for the hard X-rays.

### III. Physical Properties of the Hard X-Ray Source

As discussed in the introduction, several observers have detected hard X-rays from Sco X-1. In the calculations below we use the recent measurements of Haymes et al. (1972) which indicate that the X-ray flux density above about 30 keV from Sco X-1 can be equally well represented by a power law or an exponential:

$$\phi(E) \text{ (keV cm}^{-2}\text{sec}^{-1}\text{keV}^{-1}\text{)} = \begin{cases} 0.4E^{-(0.8 \pm 0.3)} \\ 0.02\exp[-E/190(+180, -90)] \end{cases}, \quad (8)$$

where E is in keV. At a distance of 170 pc, the luminosity in these X-rays from 30 to 300 keV is  $\sim 1.3 \times 10^{34} \text{ erg s}^{-1}$ . This should be compared with the total observed luminosity of Sco X-1, which at the same distance is  $\sim 2 \times 10^{36} \text{ erg s}^{-1}$  (Westphal, Sandage and Kristian 1968).

If we assume that the hard X-rays are produced by bremsstrahlung at an effective temperature  $T \approx 190 \text{ keV/k} \approx 2 \times 10^9 \text{ K}$ , then from the formula for the total free-free emission of a hot plasma (Allen 1963), we find that the emission measure (defined as the product of the volume times the mean square electron density) is

$$EM \approx 2 \times 10^{56} \text{ cm}^{-3}. \quad (9)$$

Such a large emission cannot be produced by the radio-emitting electrons of Figure 1. For the parameters of this source, the maximum value for EM would be about  $4 \times 10^{53} \text{ cm}^{-3}$  (for  $r = 3 \times 10^{13} \text{ cm}$  and  $n_r(>30 \text{ keV}) = n = 2 \times 10^6 \text{ cm}^{-3}$ ). This value of EM is smaller by about a factor of 500 than the emission given in equation (9).

It can also be shown (Appendix B), that the radio emitting electrons cannot produce the hard X-rays by the Compton process in the radio source. Haymes et al. (1972) have already concluded that it is very unlikely that the hard X-rays are synchrotron radiation. We therefore proceed with the assumption that the hard X-rays are produced by bremsstrahlung in a physical region lying between the main X-ray source (at  $r \lesssim 10^9 \text{ cm}$ ) and the radio source (at  $r \gtrsim 10^{12} \text{ cm}$ ).

Bremsstrahlung X-rays could either be thermal or nonthermal. For nonthermal bremsstrahlung, only a small fraction of the energy of a fast electron goes into radiation, the rest being lost as ionization and heat. This fraction is a strong function of the energy of the electron; it also depends weakly on the state of ionization of the ambient medium. At 100keV it is about  $10^{-4}$  in neutral hydrogen (Berger and Selzer 1964) and about  $3 \times 10^{-5}$  in ionized hydrogen.

Therefore, if the hard X-rays are produced by nonthermal bremsstrahlung, the total energy loss involved in their production is about  $(1 \text{ to } 2) \times 10^{38} \text{ erg s}^{-1}$ , a value larger by about a factor of 50 to 100 than the total observed luminosity of Sco X-1. In this case the excess energy would have to be released in a hitherto unobserved part of the spectrum, or as mass loss. While both these possibilities

remain open, we shall not discuss nonthermal bremsstrahlung any further, because, as we shall show below, the hard X-rays can be produced by thermal bremsstrahlung with less expenditure of energy.

For thermal bremsstrahlung, the temperature in the hard X-ray emitting region is  $T \approx 2 \times 10^9$  K. If we assume spherical symmetry about the central star, the energy flux due to conduction between this region and the region which produces the main X-ray component is

$$\left(\frac{dW}{dt}\right)_c \approx K_0 T^{5/2} \frac{\Delta T}{\Delta r} 4\pi r^2, \quad (10)$$

where  $K_0 T^{5/2}$  is the coefficient of heat conduction, and  $K_0 = 5 \times 10^{-7}$  in cgs units (Brandt and Hodge 1964). If  $\Delta T/\Delta r \approx T/r$  and if  $T \approx 2 \times 10^9$  K, then  $(dW/dt)_c \approx 2 \times 10^{27} r \text{ erg s}^{-1}$ . In order for this flux not to exceed the total luminosity of Sco X-1, we must have that  $r \lesssim 10^9$  cm.

A possible temperature distribution that is consistent with this result is shown in Figure 2. For  $r > 10^9$  cm,  $T = 2 \times 10^9$  K. From considerations of the main X-ray component,  $T = 4 \times 10^7$  K at  $r = 4 \times 10^8$  cm (Kitamura et al. 1971). From the fact that optical line emissions were observed from Sco X-1, it follows that the temperature just outside the main X-ray component must drop below  $\sim 10^5$  K (Tucker 1967). The gross features of the temperature distribution in the  $4 \times 10^8 \lesssim r \lesssim 10^9$  cm region are shown by a dashed line in Figure 2.

The line labeled  $T_{esc}$  in Figure 2 is the temperature a proton would have if its thermal velocity equals its escape velocity at a

given value of  $r$ . (We assume that the mass of Sco X-1 equals  $1 M_{\odot}$ ). It is known from studies of the solar corona (Parker 1965) that a temperature distribution as shown in Figure 2 leads to an atmosphere that expands into space with steadily increasing velocity as thermal energy is being converted into kinetic energy of bulk motion and potential gravitational energy. The plasma velocity reaches the sound speed at a distance  $r_c$  from the center of the star where the escape velocity of the protons equals their thermal speed. The distance is given by

$$r_c \approx \frac{2GM m_p}{3kT}, \quad (11)$$

where  $G$  is the gravitational constant,  $M$  is the mass of the star,  $m_p$  is the proton mass, and  $T$  is the temperature at  $r_c$ . The condition for supersonic expansion is that  $r_c$  be located in a physically accessible point. If the temperature is too high,  $r_c$  is below the surface of the star; if the temperature is too low the escape velocity is always greater than the thermal velocity. In both cases the atmosphere will not expand supersonically (e.g. Dessler 1967).

For Sco X-1,  $r_c$  lies somewhere between  $4 \times 10^8$  cm and  $10^9$  cm, and the condition for supersonic expansion appears to be fulfilled. We note, however, that the magnetic field at  $r = 10^9$  cm should be less than about  $10^5$  gauss, because otherwise the energy density in the magnetic field will exceed that in the thermal plasma and supersonic expansion will not be possible. This value of  $B$  is within the range of possible magnetic fields extrapolated from the radio emitting region to



$r = 10^9$  cm (see previous section). We conclude therefore that there could be a mass flow or stellar wind for Sco X-1.

If the stellar wind becomes supersonic at  $\sim 10^9$  cm, and if the speed of the wind  $V$  remains constant thereafter (as in the case of the solar wind), conservation of mass requires that the density should vary as  $r^{-2}$ . In order to account for the observed hard X-rays with this density variation, we must have that

$$EM = 4\pi n_0^2 r_0^4 \int_{r_0}^{r_2} dr/r^2 = 2 \times 10^{56} \text{ cm}^{-3}, \quad (12)$$

where  $n_0 = n(r_0)$  and  $r_0 = 10^9$  cm. If  $r_2 \rightarrow \infty$  then  $n_0 = 1.3 \times 10^{14} \text{ cm}^{-3}$ . However, because the density drops as  $r^{-2}$  and the electron-proton collision mean free path is inversely proportional to  $n$ , the plasma can be in thermal equilibrium only if the mean free path is less than the linear dimension of the region. We define the radius  $r_2$  as

$$r_2 \approx v_{th}(e) f_{ep}^{-1} \quad (13)$$

where  $v_{th}(e)$  is the thermal speed of the electrons and  $f_{ep}^{-1}$  is the electron-proton collisions frequency. For  $T = 2 \times 10^9 \text{ K}$ , equation (13) yields  $r_2 \approx 5 \times 10^9$  cm. If we use this value in equation (12), we get that  $n_0 = 1.5 \times 10^{14} \text{ cm}^{-3}$ , or

$$n(r) \approx 1.5 \times 10^{32} r^{-2} \text{ (cm}^{-3}\text{)} \quad (14)$$

where  $r$  is in cm. Equation (14) is plotted as a solid line in Figure 2 for  $r > 10^9$  cm.

From considerations of the main X-ray component, the density at  $r = 4 \times 10^8$  cm is  $3 \times 10^{16} \text{ cm}^{-3}$ . We can also estimate the density in the  $4 \times 10^8 \lesssim r \lesssim 10^9$  cm region from the observed H $\beta$  emission. According to Tucker (1967), the luminosity of the H $\beta$  line is about  $10^{30} \text{ erg s}^{-1}$  (for  $d = 170 \text{ pc}$ ). Since at  $T = 10^5 \text{ K}$  the H $\beta$  emissivity is  $\sim 10^{-26} \text{ n}^2 \text{ erg cm}^{-3} \text{ s}^{-1}$  (Tucker 1967), the H $\beta$  emission measure at Sco X-1 is  $\sim 10^{56} \text{ cm}^{-3}$ . For an order of magnitude estimate, we may assume that the H $\beta$  comes from a region extending from  $r = 5 \times 10^8$  cm to  $6 \times 10^8$  cm. Since the volume of this region is  $4 \times 10^{26} \text{ cm}^3$ , the r.m.s. density of the H $\beta$ -emitting gas becomes  $\sim 5 \times 10^{14} \text{ cm}^{-3}$ . This density, and the density of the main X-ray producing region are plotted as squares in Figure 2.

Let us now evaluate the effects on the radio emission of the ambient density as given by equation (14). From Figure 1 we take  $r = 3 \times 10^{12}$  cm and  $B_{\perp} = 1$  gauss. By assuming that equation (14) holds for this value of  $r$  (i.e. the speed of the wind stays constant), we get that  $n(3 \times 10^{12} \text{ cm}) = 1.6 \times 10^{17} \text{ cm}^{-3}$ . From equation (3) the plasma frequency is  $\nu_p = 3.7 \times 10^7 \text{ Hz}$ . From equation (5), the Razin cutoff frequency is  $\nu_R = 8 \times 10^8 \text{ Hz}$ . Thus, the observed radio emission at  $\nu > 10^9 \text{ Hz}$  is well above the plasma frequency; the Razin cutoff, however, will have an observable effect at  $\nu \lesssim 10^9 \text{ Hz}$ .

We can also evaluate the optical depths of the radio source at  $10^9 \text{ Hz}$  due to gyroresonance absorption. From equation (6) and Table 1 we get that for  $\nu/\nu_B = 357$  ( $\nu = 10^9 \text{ Hz}$  and  $B = 1$  gauss)  $I \approx 10^{-8}$ . The

optical depth,  $\tau \approx 2\alpha r$ , is therefore 0.18. We see that gyroresonance absorption may also have an important effect on the radio spectrum at  $\nu \lesssim 10^9 \text{ Hz}$ . In fact, because the function I (from Table 1) increases rapidly with increasing B, the magnetic field cannot be larger than a few gauss. Otherwise the radio emission will be absorbed by the gyroresonance absorption.

#### IV. Mass Loss and the Ionization of the Interstellar Medium

Let us now estimate the mass and energy loss of the star due to the stellar wind. For steady state conditions, the mass loss is given by

$$\frac{dM}{dt} = 4\pi r^2 n m_p V \quad (15)$$

where  $n$  and  $V$  are the density and bulk speed at the distance  $r$ . If the protons and electrons are in thermal equilibrium, the energy loss is given by

$$\frac{dW}{dt} = 4\pi r^2 (2n) \langle E \rangle V \quad (16)$$

where  $\langle E \rangle$  is the thermal energy of a particle, and the factor of 2 takes into account the energies in both protons and electrons. We use  $r = 10^9 \text{ cm}$ ,  $n = 1.5 \times 10^{14} \text{ cm}^{-3}$ , and  $V = v_{\text{th}}(p) = 7 \times 10^8 \text{ cm s}^{-1}$  ( $T = 2 \times 10^9 \text{ K}$ ). Then equation (15) yields  $dM/dt \approx 3 \times 10^{-8} M_{\odot}/\text{year}$ . This mass loss is not excessive, particularly since the age of Sco X-1 is probably less than  $10^6$  years. For  $\langle E \rangle \approx 200 \text{ keV}$ , equation (16) yields  $dW/dt \approx 8 \times 10^{35} \text{ ergs}^{-1}$ . This energy loss is comparable with both the total luminosity of Sco X-1 and the conduction energy

flux from the hard to the main X-ray producing regions.

A consequence of the outflow of energetic particles is the ionization of the interstellar medium around Sco X-1. Indeed, Johnson (1971) did report observations of H $\beta$  emission from the vicinity of this object. Silk et al. (1972) have discussed the ionization that is produced by the known X-ray flux from Sco X-1 and concluded that it cannot produce the observed H $\beta$ , unless there exists a strong soft X-ray emission from this object.

According to Johnson (1971), the observed H $\beta$  intensity,  $I_{H\beta}$ , is about  $2.5 \times 10^5$  photons  $\text{cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ , and it comes from a region of angular radius of at least  $1^\circ$  around Sco X-1. If the H $\beta$  emission is produced by hydrogen recombinations in a region of temperature  $T$  and electron density  $n_e$ ,

$$I_{H\beta} = \frac{L}{4\pi} \alpha(T) n_e^2 \epsilon_{H\beta}, \quad (17)$$

where  $L$  is the linear depth of the region,  $\alpha(T)$  is the recombination coefficient as a function of temperature, and  $\epsilon_{H\beta}$  is probability for the emission of an H $\beta$  photon per recombination. According to Reynolds (1971),  $\epsilon_{H\beta}$  is essentially independent of temperature and equals about 0.1.

If the H $\beta$  emitting region is ionized by charged particles at a rate  $\zeta$  per hydrogen atom and if this region is in ionization equilibrium,  $\alpha(T) n_e^2 = \zeta n_H$ , where  $n_H$  is the hydrogen density. Since a fast particle expends some  $5.8 \times 10^{-11}$  erg to produce an ion pair (Dalgarno and

Griffing 1958), the power in corpuscular radiation that is required to produce the H $\beta$  emission in a spherical region of radius L/2 is

$$\frac{dW}{dt} = \frac{(4\pi)^2 I_{H\beta} L^2}{24\epsilon_{H\beta}} (5.8 \times 10^{-11} \text{ erg}). \quad (18)$$

By substituting the above values of  $I_{H\beta}$  and  $\epsilon_{H\beta}$ , and by using  $L \approx 6$  pc (corresponding to an angular radius of  $1^\circ$  at 170 pc), we get  $dW/dt \approx 3 \times 10^{35}$  erg/sec. This power should be considered as a lower limit to the total corpuscular energy loss of Sco X-1, because not all the charged particles will deposit their energy in the H $\beta$ -producing region. Also, if this region is partially ionized, part of the energy goes directly into heat rather than ionization. Nonetheless, the general agreement between the powers obtained from considerations of the properties of the hard X-ray source at Sco X-1 and the H $\beta$  emission from its vicinity, lends credence to the proposed mass outflow from this object.

Let us finally estimate the distances that the charged particles could travel from the star in the interstellar medium. The stopping ranges of 200 keV protons in neutral and ionized hydrogen are about  $10^{-4} \text{ g cm}^{-2}$  and  $4 \times 10^{-6} \text{ g cm}^{-2}$ , respectively. (We use the energy loss rates as given by Ginzburg and Syrovatskii (1964) p. 121). If the protons travel in straight lines, these ranges correspond to linear distances of  $20 \text{ pc}/n_H$  and  $0.8 \text{ pc}/n_H$ . Because these distances bracket the distance of 3 pc obtained from the H $\beta$  observations for possible values of  $n_H$ , it is reasonable to assume that a significant fraction

of the protons will stop in the H $\beta$ -emitting region.

The stopping range of a 200 keV electron is  $\sim 0.02 \text{ g cm}^{-2}$  in neutral hydrogen (Berger and Seltzer 1964), and about a factor of 4 higher in ionized hydrogen (Hayakawa and Kitao 1956). The electrons of the stellar wind will therefore escape from the vicinity of Sco X-1 with essentially no energy loss.

## Appendix A

The gyroresonance absorption coefficient due to a homogeneous and isotropic distribution of electrons with differential number density  $u(\gamma)$  in a static and uniform magnetic field is given by (Ramaty 1969)

$$\alpha(\nu) = \frac{1}{8\pi m \nu^2} \int_1^\infty d\gamma \, p(\nu, \gamma) \, \beta \gamma^2 \frac{d}{d\gamma} \left( \frac{u(\gamma)}{\beta \gamma^2} \right), \quad (\text{A1})$$

where  $m$  is the electronic mass, and  $p(\nu, \gamma)$  is the gyroresonance emissivity (in  $\text{erg sec}^{-1} \text{Hz}^{-1}$ ) of an electron. For a Maxwell-Boltzman distribution at a temperature  $T$ , equation A1 reduces to

$$\alpha = \frac{n}{(2\pi)^{3/2} \frac{m\nu}{2}} \left( \frac{mc^2}{kT} \right)^{5/2} \int_1^\infty d\gamma \, p(\nu, \gamma) \beta e^{-\frac{mc^2}{kT} (\gamma-1)} \quad (\text{A2})$$

We have evaluated equation (A2) numerically for  $T = 2 \times 10^9 \text{ K}$  and  $p(\nu, \gamma)$  as calculated by Ramaty (1968). The result is given by equation (6), where

$$I = [\sqrt{3} e^3 B / mc^2]^{-1} \int_1^\infty d\gamma \, p(\nu, \gamma) \beta e^{-\frac{mc^2}{kT} (\gamma-1)}. \quad (\text{A3})$$

## Appendix B

We show that the hard X-rays cannot be due to Compton scattering of the radio electrons with ambient photons if the radio and hard X-ray sources are physically coincident. The Compton flux density  $F_c(E)$  from an electron distribution  $A(\gamma-1)^{-\Gamma}$  which produces a synchrotron flux density  $F_s$  at a fixed frequency  $\nu$  is given by (e.g. Ramaty 1971)

$$F_c(E) \approx 4.7 \times 10^3 (15.8)^\Gamma \rho F_s(1 \text{ GHz}) \left(\frac{4E}{3}\right)^{\frac{\Gamma-3}{2}} B_\perp^{\frac{\Gamma+1}{2}} E^{-\frac{\Gamma-1}{2}} \quad (\text{B1})$$

where  $F_c$  is in  $\text{keV cm}^{-2} \text{s}^{-1} \text{keV}^{-1}$ ,  $F_s$  is in  $\text{erg cm}^{-2} \text{sec}^{-1} \text{Hz}^{-1}$ ,  $\rho$  is the incident photon density in  $\text{eV cm}^{-3}$ , and  $E_0$  and  $E$  are the energies of the incident and scattered photons in keV.

For  $T = 4 \times 10^7 \text{K}$ ,  $(4/3)E_0 = 4.6 \text{ keV}$ . From the observed main X-ray component ( $2 \times 10^{36} \text{erg/sec}$  if  $d = 170 \text{ pc}$ ), the energy density of incident photons at a distance  $R_{12}$  from the center of the star is  $\rho \approx 3 \times 10^{12} R_{12}^{-2} \text{ eV cm}^{-3}$ , where  $R_{12}$  is in units of  $10^{12} \text{cm}$ . We use, as before,  $F_s(1 \text{ GHz}) = 3 \times 10^{-25} \text{ erg cm}^{-2} \text{sec}^{-1} \text{Hz}^{-1}$  and  $\nu = 1 \text{ GHz}$ . From equation (8) (for the power law fit)  $(\Gamma-1)/2 = 0.8$ , so that  $\Gamma = 2.6$ .

Equation (B1) then yields

$$F_c(E) \approx 5.5 \times 10^{-6} R_{12}^{-2} B_\perp^{-1.8} E^{-0.8} \text{ keV cm}^{-2} \text{sec}^{-1} \text{keV}^{-1}. \quad (\text{B2})$$

Since  $R_{12} \approx 1$  and  $B \approx 1 \text{ gauss}$  from Figure 1, the Compton flux density as given by Equation (B2) is negligible in comparison with the observed X-ray flux as given by equation (8).



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Table 1

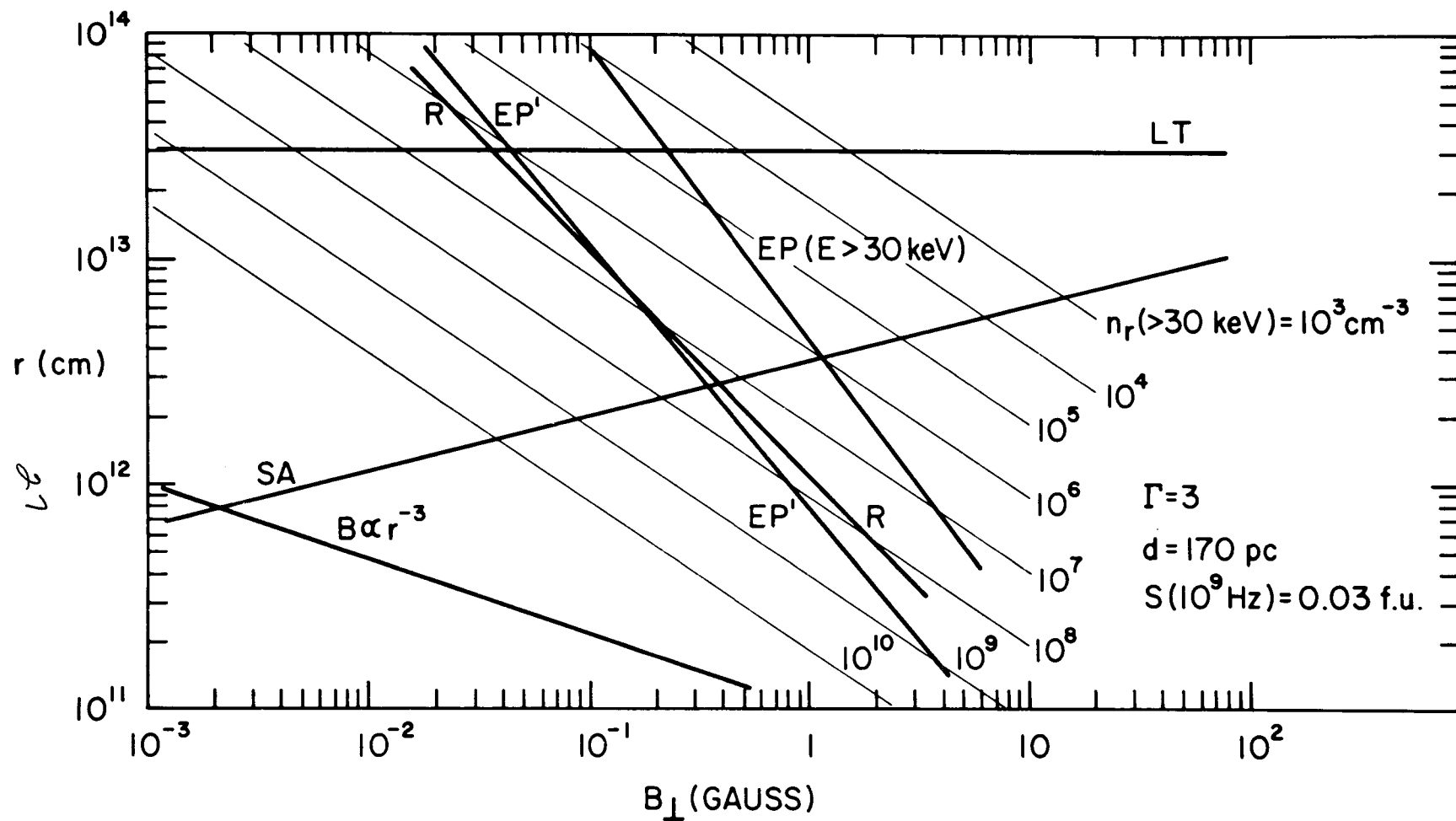
The function  $I$ , defined in equation (6), for various frequencies in units of the gyrofrequency.

$\nu/\nu_B$	$I$
100	$1.9 \times 10^{-5}$
150	$2.5 \times 10^{-6}$
200	$5 \times 10^{-7}$
250	$1.3 \times 10^{-7}$
300	$3.9 \times 10^{-7}$
350	$1.3 \times 10^{-8}$
400	$5 \times 10^{-9}$

Figure Captions

1. Radius  $r$  of the radio source as a function of the perpendicular component of the magnetic field  $B_{\perp}$ . The various lines are described in Section II.
2. Temperature and density in the atmosphere of Sco X-1. The various entries are defined in Section III.

Figure 1



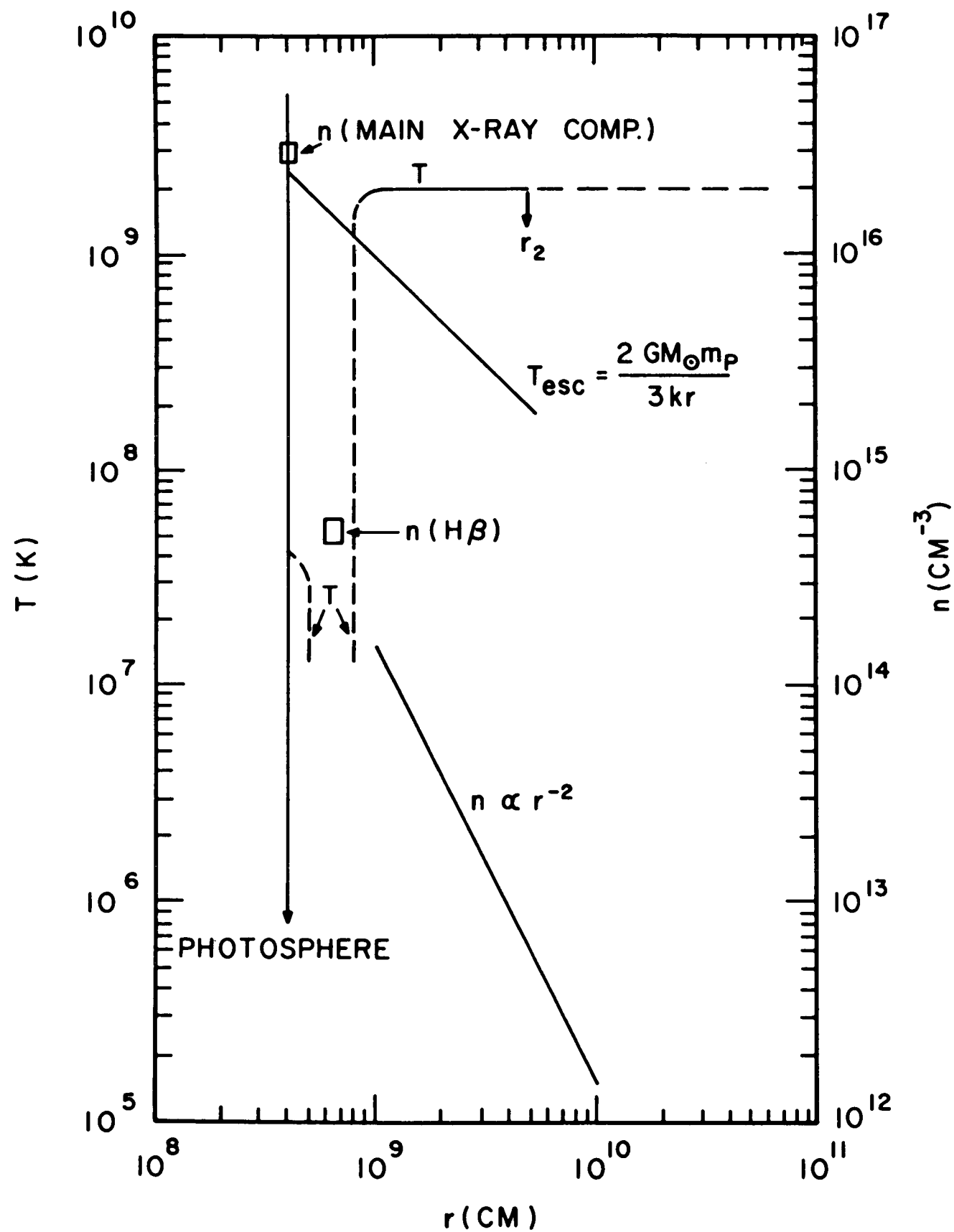


Figure 2